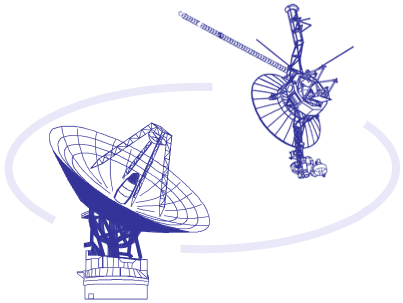
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Deep Space Optical Communications Visions, Trends and Prospects

R. J. Cesarone
D. S. Abraham
S. Shambayati
Jet Propulsion Laboratory, California Institute of Technology

J. Rush
NASA Headquarters



12 May 2011

Introduction

- Background
- Drivers: Planetary Science; Astrophysics; Human Exploration
- Data Rates & Data Rate Trends
- Spectrum
- Optical & RF Comparisons
- SCaN's *Optical Communications Roadmap*
- Early Steps
- Summary

Background

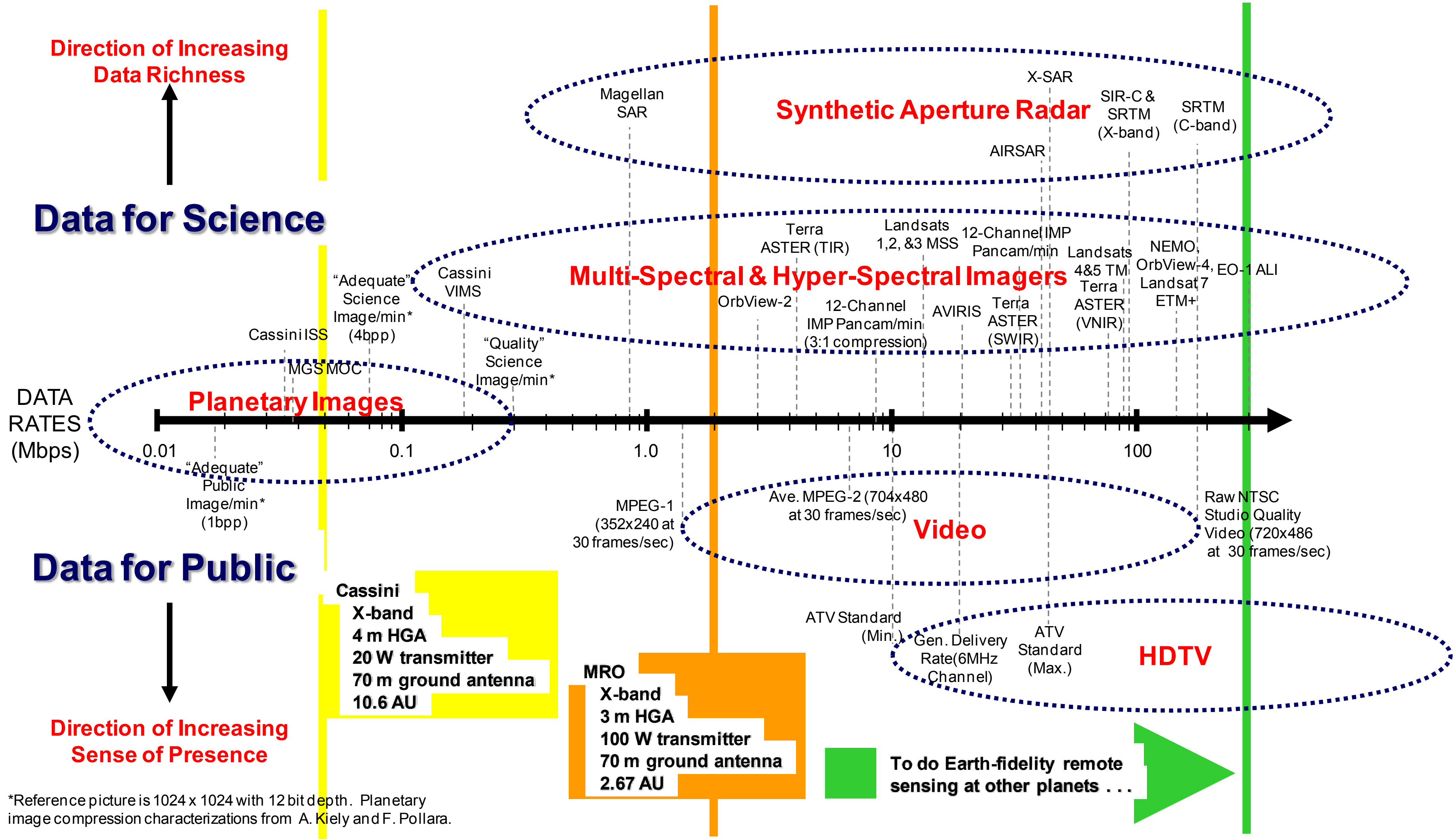
- Interest in optical communications has certainly grown since the 1980s
  - Its potential is not hard to recognize
- However, implementation, and even demonstration, has been a “hard sell”
  - Do customers really need it? Yet?
  - They’d rather exploit the remaining RF “head room”
- Customer’s demand side
  - Moving to a different class of exploratory missions
  - Rapid pace of science instrument development
  - New discoveries arise from higher spatial, temporal and spectral resolution
- Technology developer’s side
  - Technology may be leading the customer needs
  - But something new always entails more risk
  - Roles of partnership vis-à-vis competition
- Policymaker’s side
  - Can encourage or discourage customer demand
  - Outreach demand may trump science demand
- Von Braun analogy re: the state of rocketry in the early-1950s
  - Reference: "A Plea for a Coordinated Space Program," article in *The Complete Book of Outer Space*, published 1953 by the Gnome Press.

Drivers: Planetary Science

- 1980s – early-1990s: Tail end of the initial reconnaissance of the solar system
  - Most demanding deep space missions typically had D/L data rates ~10s to 100s of kbps
  - Sufficient to return first images of other planets
  - No threat to consuming allocated spectrum
  - Links were challenging but engineers still envisioned numerous RF improvements
    - Higher RF frequencies
    - Better FEC coding
    - Lower receiver noise temperature
    - Larger receiving area
    - Greater EIRP on spacecraft
- Mid-1990s - Today: Re-examine planetary targets in more detail
  - Preliminary reconnaissance of the solar system has essentially been completed
    - All planets had been visited at least once (*Note: Pluto got demoted!*)
  - Current deep space missions need D/L data rates ~100s of kbps to 10s of Mbps, i.e., more than an order of magnitude increase
    - Images: higher resolution and/or multi-spectral
    - SAR observations
    - Near R/T video
  - Remote sensing of other planets, at the same fidelity done at Earth today, requires an increase of more than three orders of magnitude

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Required Data Rates as a Function of Data Type



*Reference picture is 1024 x 1024 with 12 bit depth. Planetary image compression characterizations from A. Kiely and F. Pollara.

Other Drivers

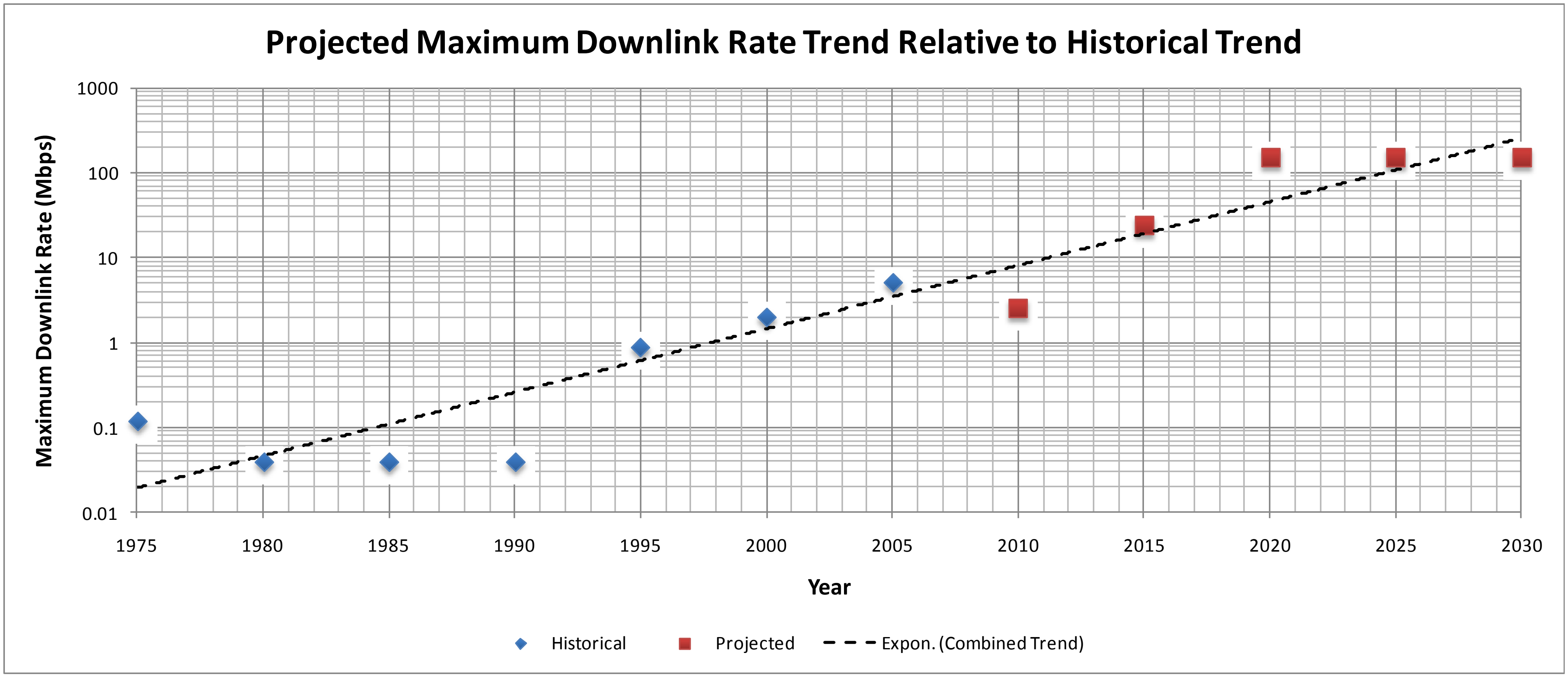
Astrophysics:

- 1990s – early-2000s: NASA's Great Observatories
  - Spitzer (IR); Hubble (Visual); Chandra (X-ray); Compton (γ-ray)
  - Typical D/L data rates: 0.5 Mbps to 2.0 Mbps
- 2010 - 2020: Greater (?) Observatories
  - JWST D/L data rates: 25 Mbps, i.e., more than an order of magnitude increase
- 2020s - ???: Greatest (?) Observatories
  - Concepts for dark energy investigation D/L data rates: 150 Mbps, i.e., ~ 2 orders of magnitude beyond the Great Observatories

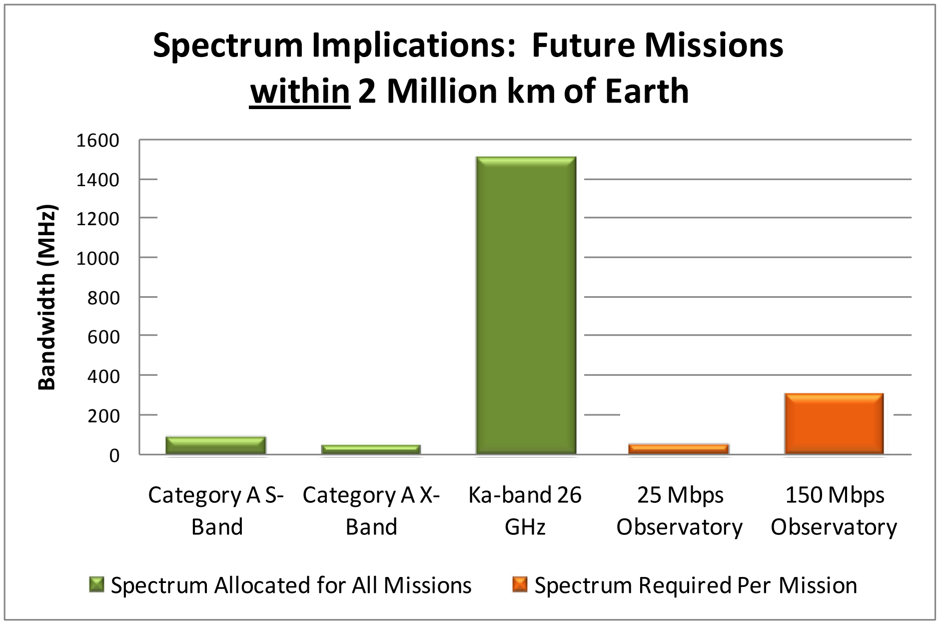
Human Exploration:

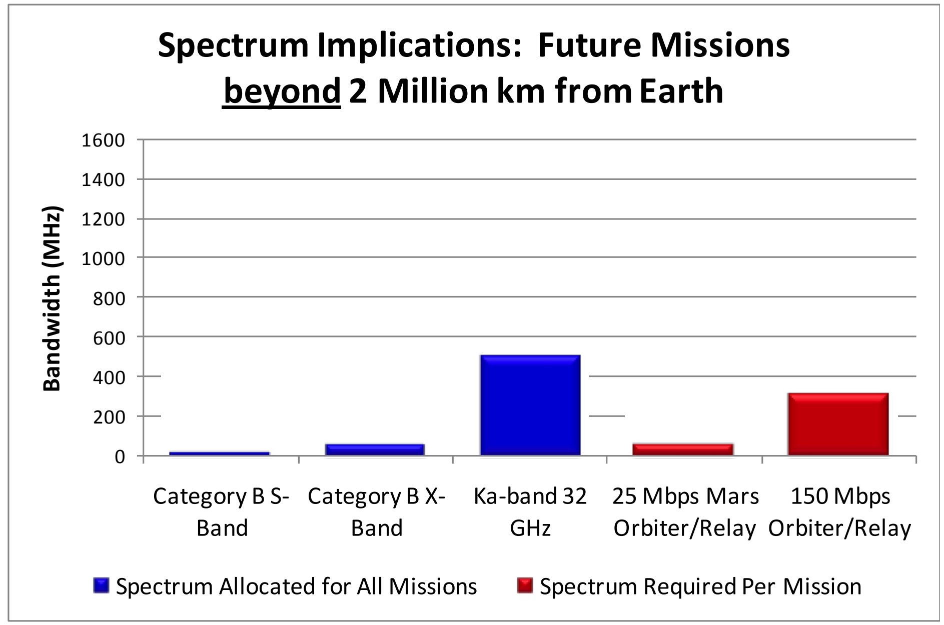
- Late-1960s – early-1970s: Apollo era
  - S-band D/L data rates: 50 kbps
- 1980s - 2020: Space Shuttle / ISS era
  - Ku-band D/L data rates: 50 Mbps
- 2020s - ???: Lunar return / Near-Earth Objects / Mars expedition
  - Anticipated Ka-band D/L data rates: 150 Mbps

Historical and Projected Downlink Rate Trend



Category A and B Spectrum Allocations Relative to High-Rate Mission Bandwidth Requirements





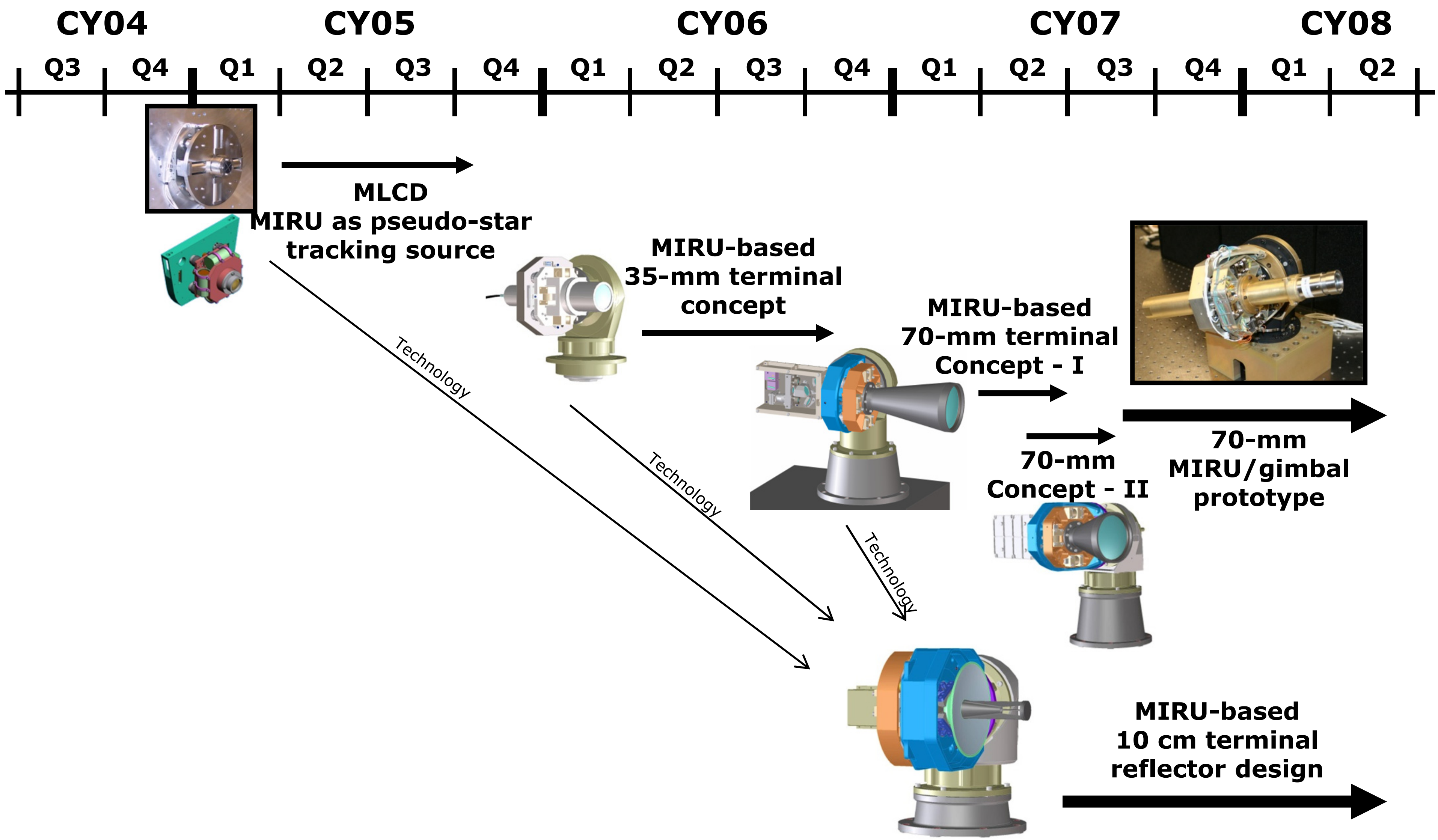
Future Downlink Possibilities at RF and Optical

	Data Rate Today		Data Rate ~2020		Data Rate ~2030		
Spacecraft Capabilities	3m Antenna X-Band 100 W Xmitter		3m Antenna Ka-Band 180 W Xmitter		5m Antenna Ka-band 200 W Xmitter		1m Optical 1550 nm 50 W Xmitter
DSN Antennas	1 x 34m	3 x 34m	1 x 34m	Equiv to 3 x 34m	1 x 34m	Equiv to 7 x 34m	10m Optical
Mars (0.6 AU)	20 Mbps	60 Mbps	400 Mbps	*1.2 Gbps	*1.3 Gbps	*9.3 Gbps	5.5 Gbps
Mars (2.6 AU)	1 Mbps	3 Mbps	21 Mbps	64 Mbps	71 Mbps	*500 Mbps	300 Mbps
Jupiter	250 Kbps	750 Kbps	5 Mbps	15 Mbps	16 Mbps	115 Mbps	70 Mbps
Saturn	71 Kbps	213 Kbps	1.4 Mbps	4 Mbps	4.7 Mbps	33 Mbps	19 Mbps
Neptune	8 Kbps	24 Kbps	160 Kbps	470 Kbps	520 Kbps	3.7 Mbps	2.2 Mbps

* Reference spacecraft is MRO-class (power and antenna), Rate 1/6 Turbo Coding, 3 dB margin, 90% weather, and 20° DSN antenna elevation

** Performance will likely be 2 to three times lower due to need for bandwidth-efficient modulation to remain in allocated spectrum

SCaN Optical Program Background

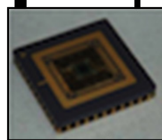


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

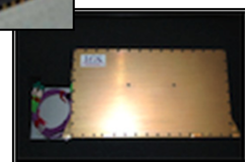
SCaN Deep Space Optical Program Background

CY04 CY05 CY06 CY07 CY08 CY09 CY10 CY11

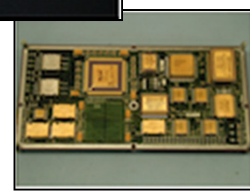
MLCD through PDR



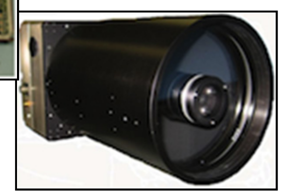
Photon counting detectors



High peak-to-average power lasers



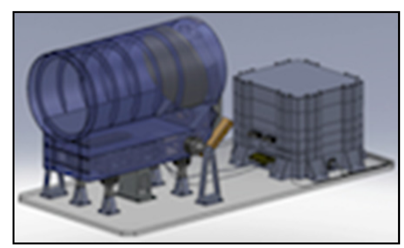
Low-power, high-speed electronics



15 cm prototype terminal

Low-frequency vibration isolation platform

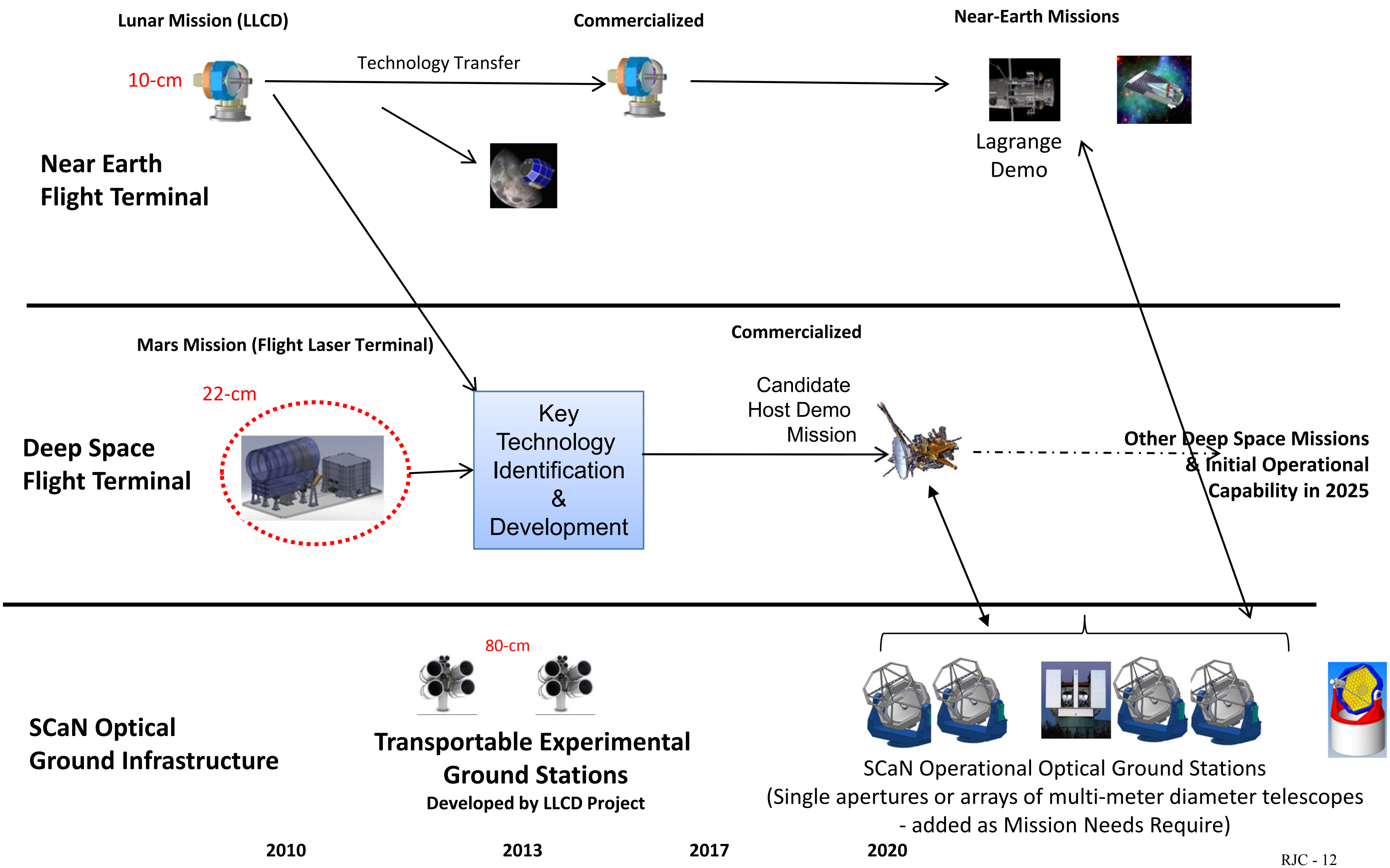
Technology



20 cm flight terminal design

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

NASA Strategy for Optical Communications Development

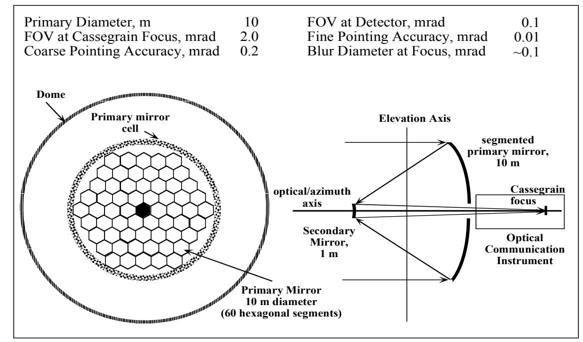


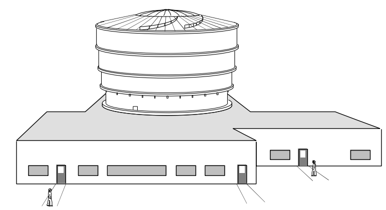
SCaN's Top-Level Demonstration Objectives

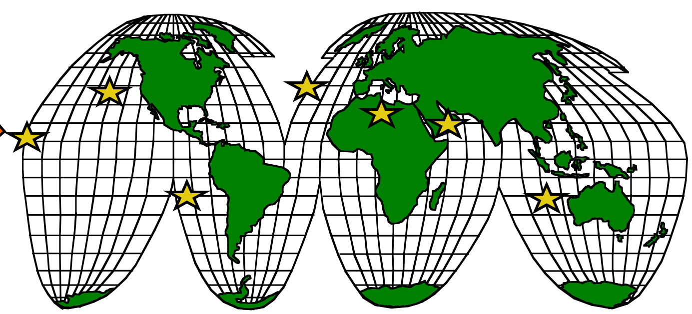
Objective	LLCD	Lunar Lander	L1	L2	Mars
High Data Rate (10X RF)					
Pointing, Acquisition & Tracking for Lunar/L1/L2					N/A
Pointing, Acquisition & Tracking for Deep Space					
Day Time Reception at Ground Terminals					
Low SEP Downlink Acquisition					
Low SPE Uplink Beacon Acquisition					
Lifetime in space					
Weather & Ground Station Handover					

1993 Ground-Based Antenna Technology Study (GBATS)

- Spatially-diverse network of optical ground stations
- 10m diameter, segmented aperture photon buckets
  - Also included 1m uplink telescope stations
- Station and network infrastructure
- Options considered
  - Clustered Optical Subnet (COS): 3 longitude regional subnets; 3 spatially-diverse stations each
  - Linearly Dispersed Optical Subnet (LDOS): N-stations around Earth
- Study recommendations:
  - 6 to 8 station LDOS judged as best
  - Best 24-hour availability at lowest cost





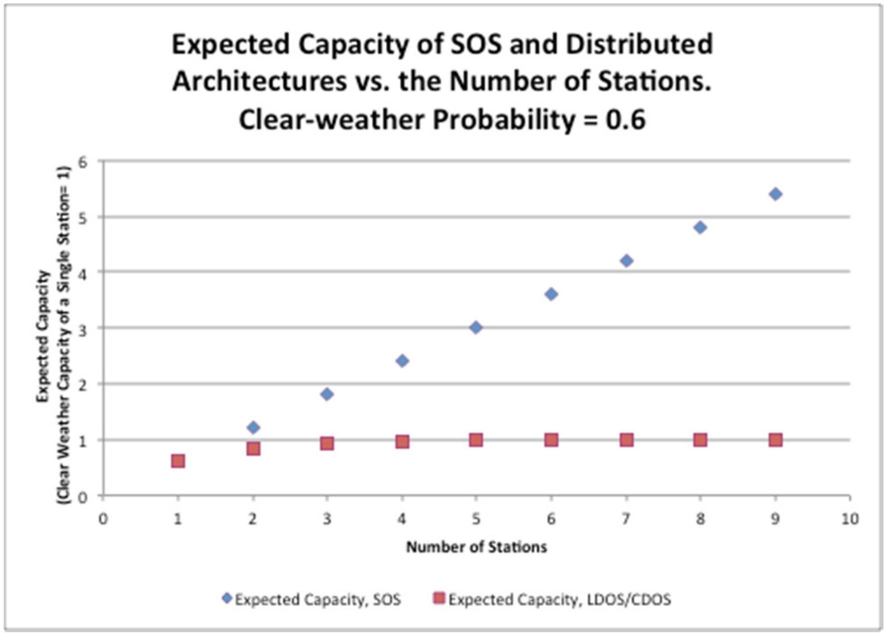


7-Station LDOS

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Early Step: Single Optical Site

- LDOS (& COS) were close to ideal ground network architectures
  - High availability enables traditional ConOps
  - But high cost and geopolitical issues remain as barriers
- Single Optical Site (SOS) proposes a ConOps paradigm shift
  - Remove (at least temporarily) requirement for high availability optical D/L
  - Replace with top-level requirement for maximization of science data return
  - Utilize optical link for high-B/W, high value but low temporal priority science data
  - Utilize RF links for routine TT&C, thumbnail science, critical event and emergency support
  - Note: SOS can always be upgraded to an LDOS or COS in the future
- SOS has some unanticipated characteristics
  - Aggregating photon collection capability at a single site is much more efficient than dispersing it to increase availability
    - 3X improvement in science data return is typical in comparison to a 5-station LDOS/CDOS architecture
  - However, provisions must be made for retransmissions with on-board solid state recorders
    - State-of-the-art in recorders is adequate – with the possible exception of Jovian radiation cases
  - Links from a Mars lander may be problematic due to nearly synchronous rotation rates of Mars and Earth



Early Step: RF-Optical Hybrid

- Modify DSN 34m X/Ka-band (8/32 GHz) antennas for reception of optical signals
  - Preliminary results show promise that dual RF-optical may be possible on the same ground terminal
  - Operational and cost benefits can result from dual use of the same aperture
  - The *utmost* in network integration - a current priority for the SCaN Office
  - Antennas being considered have: robust backup structures; large collecting areas; and millidegree pointing - all of which support optical communications
- Candidate design concept: polish / coat the inner 26m-diameter aluminum panels of a 34m antenna to a high degree of reflectivity
  - Though panels are optically smooth, they will still have underlying surface imperfections
    - Will generate large (several cm) spots at the Cassegrain focus corresponding to a FOV of hundreds of μrad
  - Large-area photon-counting-detector arrays convert the optical fields to photon counts for downstream digital processing.
  - A solar energy filter over the main reflector protects the antenna from sunlight and the panels from dust.
- Candidate design concept: replace some panels with optical reflectors
  - Optical surfaces (either monolithic or arrayed) have aperture equivalent to a 10m terminal
  - Relies on high-quality glass mirrors that replace a fraction of the aluminum panels of the antenna
  - Achieves a much smaller optical FOV while still maintaining adequate RF performance
    - Mirrors will generate much smaller spots, typically limited by turbulence to ~50 μrad FOV.
  - Use of spherical mirrors, given large overall antenna focal length, reduces implementation cost.
  - As in the other concept, a solar energy rejection filter provides protection from heat and dust.

Two Other Relevant Factors: One a minus; the other a plus

- Data, more data and even more data!
  - Data generation by missions, as well as by ground based investigations, continues to grow exponentially
  - Are we already awash in too much data?
  - Can we process all these data and mine them for useful knowledge?
  - Does it make sense to archive Tbytes of data that no one will ever examine?
  - If future mission operations concepts pre-select a small subset of collected data for downlink, that could reduce support for optical communications

- Commercial industry and spectrum
  - Demand for microwave spectrum by commercial entities seems to be insatiable
  - If deep space RF spectrum allocations become threatened, that could increase support for optical communications

Meet the New Competitors for RF Bandwidth!

- UAV use is proliferating; their ISR data transfer needs are driving a migration to X- and Ka-band.
- More "hot spots" around the globe are driving up VSAT requirements and associated bandwidth demand.
- Military and commercial information devices are growing smaller and more ubiquitous, with some of the supporting links driving up bandwidth demand. Extended Ku-band already being eyed. Ka-band next.
- Government use of commercial space assets growing to ensure network resilience.
- Commercial satellite providers increasingly offering hosted payloads to government users


Credit: USAF Courtesy Photo


Credit: NASA Ames Research Center


Credit: U.S. Navy, Photographer's Mate 2nd Class Daniel J. McLain (RELEASED)


Credit: U.S. Air Force photo/Bobbi Zapka


Credit: NASA Ames Research Center


Credit: U.S. Navy, Photographer's Mate 2nd Class Daniel J. McLain (RELEASED

Summary

- Justification for deep space optical communications is abundantly clear – at least to us!
  - Ever-growing mission requirements for data rates
  - Spectrum needed to accommodate such rates
- However, RF communications still have some potential for growth
  - Missions will prefer to exploit this rather than make the riskier leap to optical links
- Ultimately, there will be no alternative to optical communications
  - 'Ultimately' can be a long time; need to make things happen sooner
- Two strategies inherent in the SCaN *Optical Communications Roadmap*
  - Continue to invest in technologies that will improve performance, operability, risk and cost
  - Validate these technologies via demonstrations in the relevant environments
- Explore novel ConOps that may lower the cost of optical systems – in essence reducing the barriers to entry
  - This might not provide the ideal capability at the start
  - It can provide a foundation upon which to grow for the future
- Von Braun analogy
  - Although prospects may appear bleak at times, the "window of opportunity" will open
  - You have to be ready when it does!